

R-parity violation in split supersymmetry

Sudhir Kumar Gupta^{a,1}, Partha Konar^{b,2} and Biswarup Mukhopadhyaya^{a,3}

^a*Harish-Chandra Research Institute, Chhatnag Road, Jhusi,
Allahabad - 211 019, India*

^b*Department of Theoretical Physics, Tata Institute of Fundamental Research,
Homi Bhabha Road, Mumbai 400005, India*

Abstract

In the recently proposed ‘split supersymmetry’ scenario, the squark and slepton masses are allowed to be at a high scale while the gauginos and Higgsinos are within a TeV. We show that in a theory with broken R-parity, the parameter space of such a scenario allows a situation where the lightest neutralino is still stable on the cosmological scale and can be a dark matter candidate. We also separate the cases where (a) it may be invisible but not a dark matter candidate, or (b) it may decay showing a displaced vertex. It is also emphasized how the constraint on the simultaneous violation of baryon and lepton numbers gets relaxed in this scenario.

PACS : 12.60.Jv, 95.35.+d, 14.80.Ly

Keywords : Split Supersymmetry, Lightest supersymmetric particle, Broken R-Parity.

¹E-mail: guptask@mri.ernet.in

²E-mail: konar@theory.tifr.res.in

³E-mail: biswarup@mri.ernet.in

The quest for a supersymmetric nature is several decades old now [1]. Keeping the hierarchy problem in mind, the proponents of supersymmetry (SUSY), as well as those involved in devising search strategies for it, have assumed all along that the SUSY breaking scale is on the order of a TeV, where the masses of all the superpartners of the standard model particles should lie. However, some recent attempts have sought to find alternatives to this assumption. These resort to a so-called *split-supersymmetry* scenario [2]. The main features of this scenario and the arguments leading to it can be summarised as follows:

- Although SUSY helps us avoid fine-tuning the Higgs mass, a broken SUSY almost invariably leads to a large cosmological constant, the escape from which is fine-tuning of a more severe kind [3].
- If one appeals to the ‘landscape scenario’ in string theory [4], where different choices of the string vacuum give rise to a very large number of possible universes, then it may not be too improbable [5] that we reside in one of them where the cosmological constant is small enough to allow galaxy formation.
- Under such circumstances, the Higgs mass which requires a smaller degree of fine-tuning than the cosmological constant may also be probabilistically not too ‘unnatural’.
- This frees SUSY (which, among other things, may be part of nature as a necessary ingredient of superstrings and may also be helpful in building Grand Unified Theories (GUT) [6]) from the requirement of being broken within the TeV scale. A higher SUSY breaking scale, shown to be consistent upto about 10^{13} GeV, implies squark and slepton masses of similar order, thereby avoiding the flavour changing neutral current problem.
- Such heavy squarks and sleptons do not affect the unification of coupling constants since they form complete GUT multiplets [7]. One of the ways to ensure this is to have the gauginos and Higgsinos within the TeV scale. While the viability of such a spectrum and its observable consequences have already been studied [8, 9, 10], it is agreed that SUSY phenomenology in such cases should revolve around these lighter particles. The lightest neutralino which is the lightest SUSY particle (LSP) is in the right mass range to become a dark matter candidate. While the electroweak gauginos and Higgsinos can decay within a detector, heavy squarks render the gluino necessarily long-lived. Based on cosmological implications of a long-lived gluino, an upper bound of about 10^{13} GeV on the SUSY breaking scale has been suggested [2]. In the Higgs sector, some ‘fine-tuning’ (which is no more an untouchable concept) is done to keep all physical scalars

excepting the lightest neutral one heavy, and still implement electroweak symmetry breaking at the requisite scale.

Only the fields included in the minimal SUSY standard model are assumed to control the phenomenology in most of these studies (except in [8] where it is shown that some fields from the SUSY breaking sector might have a role to play). Here we examine what happens if there is baryon/lepton number violation incorporated in this scenario. In other words, we explore some features of the phenomenology associated with R-parity violation in the split SUSY model.

The MSSM superpotential, written in terms of the Higgs, quark and lepton superfields, is given by

$$W_{MSSM} = h_{ij}^l L_i H_1 E_j^c + h_{ij}^d Q_i H_1 D_j^c + h_{ij}^u Q_i H_2 U_j^c + \mu H_1 H_2 \quad (1)$$

where H_1 and H_2 are respectively the Higgs doublets that lend mass to the down-and up-type quarks. i, j etc. are family indices. Now, if $R = (-)^{(3B+L+2S)}$ is not conserved, then the superpotential admits of the following additional terms [11]:

$$W_{\mathcal{R}_p} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} \bar{U}_i D_j^c \bar{D}_k + \epsilon_i L_i H_2 \quad (2)$$

where the terms proportional to λ_{ijk} , λ'_{ijk} and ϵ_i violate lepton number, and those proportional to λ''_{ijk} violate baryon number. The constants λ_{ijk} (λ''_{ijk}) are antisymmetric in the first (last) two indices. We are assuming at the beginning of this analysis that the bilinear terms $\epsilon_i L_i H_2$ are not present. We shall later comment on their possible implications. Also, the simultaneous existence of the L-and B-violating terms can normally lead to fast proton decay, and very strong constraints on the products of such terms have been derived [12]. Again, we shall show at the end how such constraints fare in the split SUSY scenario.

In general, the lightest neutralino ($\tilde{\chi}_1^0$) is unstable as a result of the trilinear interactions. For example, we can see from figure 1 how $\tilde{\chi}_1^0$ decays into three-body final states, driven, for example, by the λ' type interactions [13]. This usually destroys the potential of the LSP as a dark matter candidate.

In the case of split SUSY, however, the situation is somewhat different. Decays of the LSP, driven by any of the trilinear R-violating couplings, necessarily involves squark or slepton propagators. This causes a large suppression in the decay rate of the LSP, and, the higher the SUSY breaking scale (M_S) is, the more long-lived it will be. Therefore, we are faced with a situation here where lepton/baryon number violation does not prevent one from having a SUSY dark matter candidate, at least in certain regions of the parameter space.

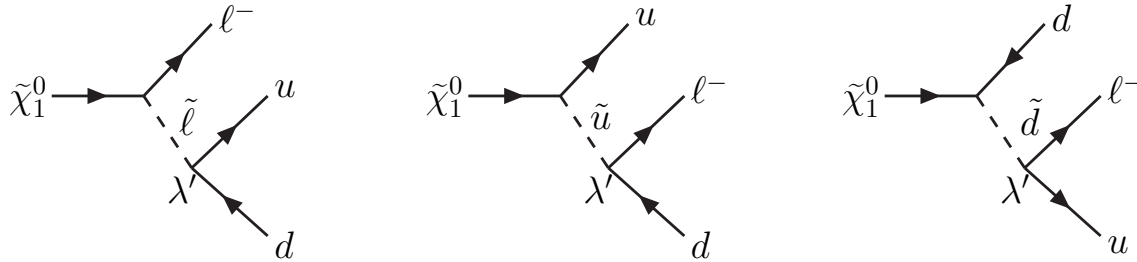


Figure 1: Representative Feynman diagrams for neutralino decay via λ'_{ijk} vertices.

The lifetime of the LSP depends on (a) the R-parity violating coupling(s) and (b) the squark/slepton masses. It should be noted that the experimental upper limits on the various couplings of the λ , λ' and λ'' -types found in the literature [14] get considerably weakened and may even disappear when the sfermions are heavy. Also, in our analysis we are taking *one* coupling of a given type at a time.

Two quantities that are likely to carry the implications of a slowly decaying LSP are (a) the lifetime of the neutralino, and (b) its decay length. In calculating them, we have taken the typical case of an LSP traveling with an energy of 250 GeV; for any other energy the corresponding quantities are easily calculable using the appropriate boost factors. Also, the properties of the LSP are controlled by the SU(2) gaugino mass M_2 , the Higgsino mass parameter μ , and $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. Gaugino mass unification has been assumed. We have used $\tan\beta = 10$. Two sets of values of the other two parameters, namely $M_2 = 200$ GeV, $\mu = 1000$ GeV, and $M_2 = 500$ GeV, $\mu = 150$ GeV, are used to demonstrate the results. These correspond to the gaugino-and Higgsino-dominated LSP, respectively.

Figures 2(a) and 2(b) show us the results for the λ' and λ'' -type couplings. Only one coupling of a given type is present in each case, and all decay products arising from that particular coupling have been summed over.

In each case, the figures demonstrate regions of the parameter space corresponding to the following possibilities:

1. The lifetime of the LSP is greater than 14 billion years, estimated to be the age of the universe [15].
2. The lifetime is less than the above value, but the decay length is more than 5 meters.
3. The decay length is more than 10 millimeters but less than 5 meters.
4. the decay length is less than 10 millimeters.

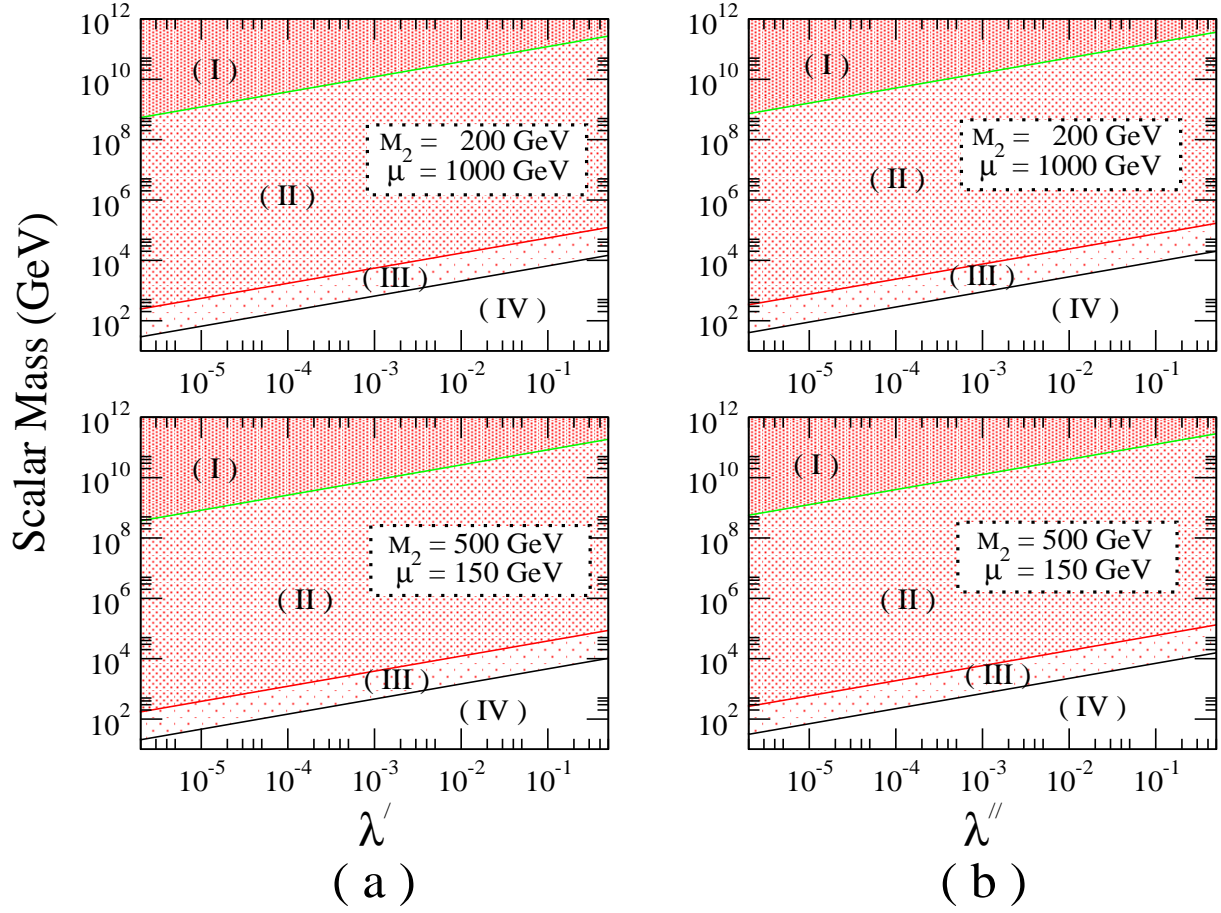


Figure 2: Regions corresponding to different decay rates of the lightest neutralino in R -parity violating models, with (a) λ' -type and (b) λ'' -type interactions. Both the cases for 'Bino' ($M_2 = 200$ GeV, $\mu = 1000$ GeV) and 'Higgsino' ($M_2 = 500$ GeV, $\mu = 150$ GeV) type LSP are shown. See text for explanation of regions I-IV. In all cases, neutralino energy = 250 GeV. $\tan\beta = 10$.

Case (1) corresponds to region I in each figure. This is seen to happen for scalar masses (or the SUSY breaking scale) between 10^9 and 10^{11} GeV, while the R -parity violating interactions varies over a wide range. We can see from this figure that however large the L- or B-violating interactions are, the LSP lifetime will exceed the age of the universe, due to the massive scalar propagators. Therefore, the lightest neutralino will continue to remain a dark matter candidate.

Case (2), represented by region II, is where the decay length exceeds the order of the radius of the hadron calorimeter in, say, the ATLAS detector at the Large Hadron Collider (LHC) [16]. The minimum scalar mass required for this varies approximately between 1 TeV and 100 TeV, as the R -parity violating coupling ranges from 10^{-6} to 1. It is expected that an LSP in this region of the parameter space has a large probability of being invisible in accelerator experiments, in spite of R -parity violation. However, since its average lifetime

is less than the age of the universe, this ‘invisible’ particle still cannot be a dark matter candidate.

Region *III* shows the region where the decay length is between 10 millimeters and 5 meters. This is a conservative description of cases where the LSP is not only visible but also shows a displaced vertex due to the suppression of its decay width by the relatively large scalar masses. Depending on the value of the coupling, this feature can be observed for the SUSY breaking scale upto about 10 TeV or slightly above.

Finally, in region *IV* one has an LSP of very small decay length which makes it unstable within a very short distance scale. This is where the usual phenomenology of weak-scale SUSY with R-parity violation is observed. It should be noted that the bottom right-hand corner regions of the graphs, representing small scalar masses but large R-violating couplings, can often be ruled out by phenomenological constraints, depending on the particular interaction.

In order to say that region *I* corresponds to neutralino dark matter, one must also ensure that we have the right relic abundance arising out of it. Such an analysis has already been performed in the literature [17],[18]. The contribution to relic abundance is governed by two factors, namely, the abundance of LSP’s arising from gravitino decay/scattering, and the rate of their annihilation. As has been shown, for example, in reference [17], this translates into a constraint on the gravitino mass if one stipulates specific values of the scalar mass and the LSP mass. A larger LSP mass for a given scalar mass necessitates a higher value of the gravitino mass. It can also be seen from the same reference that an LSP of mass ≥ 100 GeV (i.e. in the range used in this paper) is ‘safe’ from this standpoint so long as the gravitino mass is few times 10^5 GeV or above. It is also to be noted that the annihilation rate for the (stable) neutralinos corresponding to region *I* is not affected by R-parity violating couplings of the trilinear type, since no diagram driven by them leads to neutralino annihilation. For bilinear R-parity violation, on the other hand, there is mixing between neutralinos and neutralinos, and thus additional annihilation channels mediated by the W and the Z opens up. This actually can further relax the constraints on the parameter space of the scalar and LSP masses. However, as will be seen later in this paper, a bilinear R-parity violating scenario is unlikely to provide a SUSY dark matter candidate at all.

It may also be asked whether the (late) decays of the LSP can give rise, say, to photons at a late stage, and cause an unacceptable diffuse photon background. However, this is possible if there is a substantial branching ratio for the lightest neutralino decaying into a photon and a neutrino. As has been shown, for example, in reference [19], this branching ratio is very small over most of the parameter space, especially for $m_{LSP} \geq 100$ GeV. Therefore, it is not expected to pose any major problem. The other final states arising from LSP

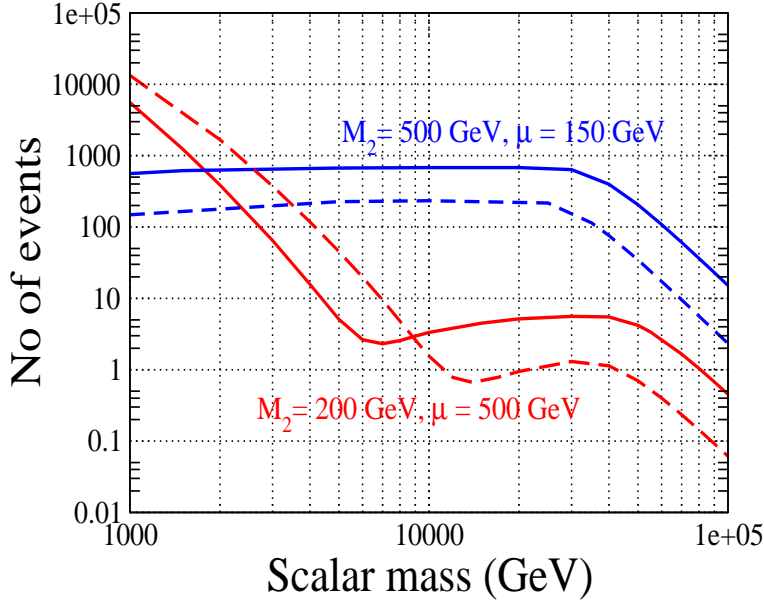


Figure 3: *The variation of number of neutralino decay events detectable within the detector in a linear collider. Solid line : CM energy = 500 GeV, dashed line : CM energy = 1000 GeV. $\tan\beta = 10$. An integrated luminosity of 500 fb^{-1} has been assumed. The value of the R -parity violating coupling is set at 0.1*

decays mostly give rise to particles which are either unstable on a cosmological scale or have high annihilation rates. However, a detailed investigation may need to be undertaken to understand all implications of such final states. Such an investigation is the subject of a separate project.

On closer scrutiny, however, region *II* (particularly the lower part of it) does not always correspond to an invisible LSP. For a particle of decay length L , the probability of its decay within a distance x is given by

$$P(x) = (1 - e^{-x/L}) \quad (3)$$

Therefore, a certain fraction of the LSP's produced must decay within the distance characterising the size of the detector, even though it happens to be smaller than the decay length. The degree of visibility thus acquired by the LSP depends on not only the factors determining its decay length but also the production cross-section and luminosity in the particular experiment.

In figure 3 we show the number of LSP decay events seen within a distance of 5 meters from the production point, for various values of M_S . In order to give a general idea, we have confined ourselves to pair-production in the process $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ at a linear electron-

positron collider, with either of the two χ_1^0 's decaying within the specified distance. Two values of the center-of-mass energy, namely 500 GeV and 1 TeV, are used, and the luminosity is taken to be 500 fb^{-1} . For each energy, we consider two points in the neutralino parameter space, in one of which the LSP is gaugino-dominated, and in the other, Higgsino dominated. In the former case, the s-channel production of the lightest neutralino pair is more hopelessly suppressed, not only because of the usual s-channel suppression at high energy, but also because the LSP coupling to the Z-boson has to depend on its very small Wino content. Therefore, the suppression of the event rate with a rise in M_S is more drastic. For a Higgsino-dominated LSP, on the other hand, there is a stronger s-channel coupling involved, making the contributions somewhat bigger even for relatively large values of M_S . Also, the event rates presented here are without any cuts. If we remember that in practice they are going to be further subjected to cuts and that various detection efficiencies are involved in obtaining the finally counted rates, the overall conclusion is that while a gaugino-dominated LSP indeed becomes invisible for M_S exceeding a few TeV's, a Higgsino dominated one can still exhibit a noticeable number of decay events for the SUSY breaking scale approaching 10^5 GeV or thereabout.

Finally, we would like to point out that the split SUSY scenario also relaxes the constraints on R-parity violation from proton decay. Such constraints generally lead one to rule out the simultaneous existence of L- and B-violating terms in the superpotential. On closer examination, one may obtain extremely stringent limits on the products of the two kinds of couplings, for SUSY broken within the TeV scale. For example, one gets [12]

$$\lambda'_{11i}\lambda''_{11i} \lesssim 10^{-27} \frac{\tilde{m}^2}{(100 \text{ GeV})^2} \quad (4)$$

It is immediately obvious that a scenario that allows the scalar masses to be much larger will dilute the above constraint, or cause it to disappear altogether. For example, one can stretch the product to values as high as, say, 10^{-11} , for $M_S \geq 10^{10}$ GeV. This corresponds to a case where one has simultaneous (though small) baryon and lepton number violation and still a stable proton, while the LSP is still invisible (with or without being a dark matter candidate).

In our discussion, we have so far left out the bilinear lepton number violating terms $\epsilon_i L_i H_2$ in the superpotential. Such terms, of course, have been of considerable interest in the recent past [20], in connection with a wide class of phenomena ranging from neutrino masses to special collider signatures. It has also been shown that even if one has just trilinear couplings at a high scale where SUSY breaking takes place, the bilinears are radiatively induced in the low-energy Lagrangian [21]. In presence of the bilinears, the scalar potential also develops additional terms, leading to non-zero vacuum expectation values for sneutrinos. On the

whole, a general consequence is the mixing between charginos and charged lepton on the one hand, and neutralinos and neutrinos on the other. As a result, the lightest neutralino can decay into a neutrino and a (real or virtual) Z or a charged lepton and a (real or virtual) [22] W. Since these decay rates are independent of scalar masses, high values of M_S will not suppress them, and the LSP will decay as quickly as is originally expected. However, this is true only if the high-scale Lagrangian itself contains the bilinears. If on the other hand they are induced radiatively from trilinears which alone are present at a high scale, then these loop-induced terms are again heavily suppressed by M_S , and the LSP decays driven by them are also correspondingly suppressed. In such a situation again the conclusions which have been drawn earlier in this paper are valid.

In conclusion, a split supersymmetry scenario can be of phenomenologically interesting consequence in relation to the violation of R-parity. They can lead to an LSP which can decay in principle but has a lifetime exceeding the age of the universe, being thus a dark matter candidate still. One can also have an unstable LSP which cannot be a dark matter candidate but still takes long enough to decay, so that it is invisible in collider experiments. It is also possible to have LSP decays showing displaced vertices. And finally, with the constraints from proton decay disappearing, the simultaneous violation of baryon and lepton numbers becomes a distinct possibility. It may be worthwhile to probe further implications of the above not only in connection with laboratory experiments but also in the cosmological context.

References

- [1] For introductory reviews see, for example, H. P. Nilles, Phys. Rep. 110 (1984) 1; H. Haber and G. Kane, Phys. Rep. 117 (1985) 75, *Perspectives on supersymmetry*, G. Kane (ed), World Scientific, 1998.
- [2] N. Arkani-Hamed and S. Dimopoulos, hep-th/0405159.
- [3] S. Weinberg, Rev. Mod. Phys. 61 (1989) 1.
- [4] S. Weinberg, Phys. Rev. Lett. 59, (1987) 2607; R. Bousso and J. Polchinski, JHEP 0006 (2000) 006; L. Susskind, hep-th/0302219; M. Douglas, JHEP 0305 (2003) 046; S. Kachru et al., Phys. Rev. D 68 (2003) 046005.
- [5] M. Douglas, hep-th/0405279.

- [6] S. Dimopoulos and H. Georgi, Nucl. Phys. B 193 (1981) 150; L. Ibanez and G. Ross, Phys. Lett. B 105 (1981) 439; M. Einhorn and D. Jones, Nucl. Phys. B 196 (1982) 475; U. Amaldi et al., Phys. Lett. B 281 (1992) 374; P. Langacker and N. Polonsky, Phys. Rev. D 52 (1995) 3081.
- [7] G. Giudice and A. Romanino, hep-ph/0406088.
- [8] B. Mukhopadhyaya and S. SenGupta, hep-th/0407225.
- [9] L. Susskind, hep-th/0405189; A. Arvanitaki et al., hep-ph/0406034; A. Pierce hep-ph/0406144; X. Calmet hep-ph/0406314; M. Dine, E. Gorbatov and S. Thomas, hep-th/0407043; P. Chankowski et al., hep-ph/0407242; E. Silverstein, hep-th/0407202; R. Mahbubani, hep-ph/0408096; M. Binger, hep-ph/0408240.
- [10] S. Zhu, hep-ph/0407072; W. Kilian et al., hep-ph/0408088; J. Hewett et al., hep-ph/0408248; L. Anchordoqui, H. Goldberg and Carlos Nunez, hep-ph/0408284.
- [11] See, for example, V. Barger, G. Giudice and T. Han, Phys. Rev. D 40 (1989) 2987, see also H. Dreiner in *Perspective in Supersymmetry* ed., G. Kane, (*World Scientific*).
- [12] J. Goity and M. Sher, Phys. Lett. B 346 (1995) 69; G. Bhattacharyya and P. B. Pal, Phys. Rev. D 59 (1999) 097701.
- [13] H. Dreiner and P. Morawitz, Nucl. Phys. B 428 (1994) 31; E. A. Baltz and P. Gondolo, hep-ph/9709445.
- [14] See, for example, B. Allanach, A. Dedes and H. Dreiner, Phys. Rev. D 60 (1999) 075014.
- [15] L. Knox et al., astro-ph/0109232; L. Krauss, astro-ph/0305556.
- [16] ATLAS technical design report, Vol.1, CERN-LHCC/99-014.
- [17] N. Arkani-Hamed *et al.*, hep-ph/0409232.
- [18] A. Pierce, Phys. Rev. D 70 (2004) 075006.
- [19] B. Mukhopadhyaya and S. Roy, Phys. Rev. D 60 (1999) 115012.
- [20] See, for example, C. S. Aulakh and R. N. Mohapatra, Phys. Lett. B 119 (1982) 136; F. de Campos et al., Nucl. Phys. B 451 (1995) 3; H. P. Nilles and N. Polonsky, Nucl. Phys. B 484 (1997) 33; S. Roy and B. Mukhopadhyaya, Phys. Rev. D 55 (1997) 7020; J. Valle, hep-ph/9808292; A. Joshipura and S. Vempati, Phys. Rev. D 60 (1999) 111303. For a general review see B. Mukhopadhyaya, hep-ph/0301278.

- [21] V. Barger et al., Phys. Rev. D 53 (1995) 6407; B. de Carlos and P. White, Phys. Rev. D 54 (1996) 3427.
- [22] B. Mukhopadhyaya, S. Roy and F. Vissani, Phys. Lett. B 443 (1998) 191.